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Published in:
Proceedings (CD-ROM)

Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

Plasma generation induced by triboelectrification

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A gas discharge plasma can be induced by triboelectrification around a sliding contact. The detailed physical mechanism of triboelectrification is unknown, but an empirical classification scheme can be referred to in practice. It is reported that intense ultra-violet emission from a plasma is observed adjacent to the sliding contact, of which the location has a gap ranging from approximately 1 μm to 11 μm. When the gap is short enough, a theory predicts that the breakdown voltage can monotonically decrease with a decrease in the gap. However, when the gap is comparable to electron's mean free path, the probability of collisions in the gap is highly suppressed, and an optimal gap may exist for the discharge ignition.

1. Introduction

Several physical processes are simultaneously induced during mechanical and tribological activation. They involve emission of photons (triboluminescence), electrons and lattice components, triboelectrification, generation of plasma (triboplasma), change of the electrical conductivity, excitation of lattice vibrations, formation and migration of lattice and electron defects, local heating-up of the solids, formation of fresh surfaces, enlargement of the surfaces, fracture processes, material abrasion, material transitions between solids, amorphization, insertion of impurities, and plastic deformation [1]. Here triboluminescence is the photo-emission caused by application of mechanical energy to a solid [2], while a triboplasma is a gas discharge plasma generated by tribological activation.

Based on the magma-plasma model [3], a severe tribological activation leads to a quasi-adiabatic energy accumulation, formation of an "energy bubble" at the deformation zone, high excitation states, strong lattice loosening, structural disruptions, detachment of lattice components, photons and electrons, and subsequent generation of a triboplasma, linking to the hot spot theory [4] or the thermal radiation model [5]. It is reported that the thermal radiation model is the essential process for the origin of continuous triboluminescent spectra associated with the photo-emission from solid materials during cutting [6]. However, a more plausible explanation for ignition of a triboplasma is due to generation of a high local electric field as a result of triboelectrification by the charge separation of opposite signs on the surfaces. It is observed during the fracture of a crystal [7,8] and the tribological interaction between dissimilar material surfaces [9-11]. It is noted that a triboplasma can be useful for the application of plasma surface modification. It is because a triboplasma can be generated by tribo-electrification without severe mechanical or tribological activation [10], and the treatment effect is expected to be similar to that of normal process plasmas [12].

In the present work mechanisms of triboelectrification and generation of a triboplasma induced by triboelectrification is discussed, reviewing experimental and theoretical studies in the literature.

2. Triboelectrification

Triboluminescence can be observed during grinding, rubbing, cutting, cleaving, compressing or impulsive crushing of materials [13]. In the case of fracture of solid materials, triboluminescence can be observed in many polymorphic-crystals with the piezoelectric forms, certain crystals, and many organic compounds, indicating that internal electrification of a material due to piezoelectric charge separation is the primary mechanism [14]. Similarly triboelectrification, the electrostatic charge accumulation by rubbing together two dissimilar material surfaces, can be an important process for inducing a triboplasma around a tribological contact [10,11]. Although the detailed physical mechanism of triboelectrification is a long unsolved problem, an empirical classification scheme "triboelectric series" is available, which classifies distinct materials in the ordering of their tendency for charge acquisition in rubbing [14,15]. The order of the triboelectric series can be affected by molecular level interaction at the contact. Coehn's law predicts that polymeric materials with lower dielectric constants tend to charge negatively, while those with higher constants do positively [16,17]. Assuming that mobile electrons are involved in charge transport, a possible explanation for Coehn's law is that materials with higher dielectric constants can be polarized and eject the electrons more easily than those with lower dielectric constants. Consequently materials with higher dielectric constants tend to charge positively, while those with lower dielectric constants negatively. It is anticipated that when the difference of the dielectric constants of contacting materials is larger, the charge transfer will be more pronounced. It is further suggested that the achievable maximum charge density at a surface may depend on the polarization within the material, and that the amount of polarization can be proportional to its dielectric constant. It is therefore expected that the charge transfer is limited by the lower dielectric constant when materials with different dielectric constants are rubbed together [18] as long as there is no ignition of a discharge. However, the ordering in the triboelectric series is different in different databases. Furthermore triboelectrification may occur even when the same materials with differing surface morphology are rubbed together. This asymmetric rubbing can induce asymmetric heating; a smaller contact area may become hotter. The concentration of mobile charged carriers increases at the hotter smaller area, and subsequently the charges tend to transfer from the smaller area to the larger. On the other hand, the asymmetric rubbing can induce a greater charge supply from a contaminant at the larger area, resulting in the charge transfer from the larger area to the smaller. Other properties at the contact surfaces can also affect the order of the triboelectric series, including presence of water, oxides, hydrocarbons, and small particles, yield strengths of materials [16,19,20], and surface damage [21]. In addition due to the existence of charge-compensating ions at the surfaces, the direction of polarization may not play an important role in electrification [22]. These tribological conditions affect triboelectrification and subsequent generation of a triboplasma. This could be the reason why expected large difference of the triboplasma was not observed with different combinations of materials [2,23].

3. Generation of a plasma by triboelectrification

A triboplasma is directly detected around a sliding contact with a pin- or ball-on-rotating disk apparatus in air at atmospheric pressure [10]. Intense infrared emission is detected at the sliding contact, indicating that the surface is heated by the friction. On the other hand intense ultra-violet (UV) emission from the N_2 gas discharge is observed adjustment to the sliding contact. The location of the intense discharge has a gap between the pin and the disk ranging from ca. 1 μm [24] to 11 μm [25]. Here the gap is estimated from the geometry of the sliding contact and the measured distance between the contact and the point of the most intense UV emission. The observed plasma is different from a triboplasma based on the magma-plasma model, which predicts that photons emit at the sliding contact induced by frictional heating or high energy states at the deformed layer beneath the contact. In addition intensity of charge emission around the sliding contact increases as an increase in resistivity of the materials [29]. It is therefore indicated that the triboplasma reported in [10,24,25,29] is induced by triboelectrification. The triboelectrification and subsequent discharging processes can be experimentally detected for further discussion of the phenomena [30].

It is important to discuss generation of a discharge in small gaps at high gas pressures in terms of failure of Paschen's law [31-41]. For example breakdown between closely separated electrodes in atmospheric pressure air is observed with potential differences down to ~50 V which is far below the minimum sparking potential voltage ~330 V at a gap ~7.5 μm in atmospheric pressure air. It is also noted that the electric field of 5 x 10^7 Vm^{-1} is too low for field emission to occur by the Fowler-Nordheim theory [31].

Paschen's law is based on the assumption that the gas breakdown process depends on the average kinetic energy of the electrons and ions accelerated by an external electric field *E,* and on the property of the gas. If the electric field *E* is uniformly distributed and if the temperature is assumed to be constant, it depends on *V*/*pd*. Here *V* and *p* are the potential difference and the pressure in a gap *d*, respectively. Townsend shows that the current *i* flowing in a uniform electric field in the potential difference *V* across the gap can be expressed by the relation:

$$i \propto \frac{e^{\eta V}}{1-\gamma\left(e^{\eta V}-1\right)} \tag{1}$$

where the coefficient η denotes the number of electrons produced per volt potential difference passed through by an electron (electron production coefficient by collision), while γ represents the number of secondary electrons per positive ion, involving one or more of several secondary mechanisms (effective electron yield per positive ion) [31,32]. The breakdown condition is formulated as:

$$\gamma\left(e^{\eta V}-1\right)=1 \quad \text{or} \quad V=\frac{1}{\eta}\ln\left(1+\frac{1}{\gamma}\right). \tag{2}$$

The electron production coefficient by collision η can be formulated as [41]:

$$\eta = \frac{Apd}{V}\exp\left(-\frac{Bpd}{V}\right) \tag{3}$$

where A and B are constants. Substituting equation (3) into equation (2) yields

$$V = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1+\frac{1}{\gamma}\right)\right]}. \tag{4}$$

At low pressures, typically $\gamma << 1$. For air, $A = 11$ Pa^{-1} m^{-1}, $B = 274$ V Pa^{-1} m^{-1} [42], and $\gamma = 0.01$. The breakdown voltage of Paschen's law for air as a function of pd is shown in Figure 1.

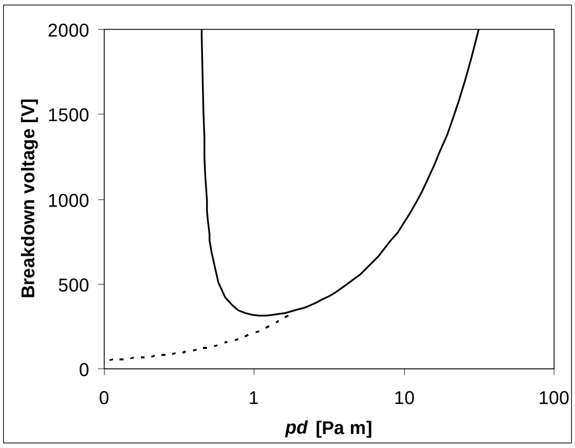

Figure 1. The breakdown voltage for air. Paschen's law (solid line) and its departure at a short gap d (dashed line. $\gamma = 4$ [39], $B = 821$ V Pa^{-1} m^{-1}).

At high pressures with a small gap the primary process for electron production is due to the combined applied and ionic space charge fields and subsequent field emission at the surfaces; positive ions approaching to the cathode would generate an ionic space charge field, decrease the width of the potential barrier, and lead to a large yield of secondary electrons [31,40,43] so as to enable the low voltage field emission. It is reported that a typical value of the electron emission coefficient of field emission γ is at least more than 1.5 in a small gap in atmospheric pressure air [35]. Under such a condition, the breakdown voltage V in equation (4) monotonically decreases with the decrease in the gap as shown in Figure 1 (dashed line). The tendency is independent of the choice of B, although it is assumed that $B = 821$ V Pa^{-1} m^{-1} so that the dashed line locates at a reasonable position in Figure 1. The decrease in the breakdown voltage at high pressure as the decrease in the gap is reported both theoretically [39] and experimentally [31,35,38]. However, when the gap d is comparable to or less than the mean free path of the electrons, the electron production coefficient by collisions η should abruptly decrease. This simple argument suggests that there can be a minimum breakdown voltage in a small gap at atmospheric pressure.

The conditions of the electrode surfaces such as materials, coatings, oxide layers [44,45], roughness [46], and the existence of particles such as dust produced during previous breakdowns [44,47-50] also influence field emission and thus the gas breakdown [33,34]. It is reported that dielectric-coated electrodes can increase the gas breakdown voltage by shielding electrode protrusions from the gas [41]. On the other hand, significantly lower threshold voltages of field emission are observed for Al_2O_3 coated Si than uncoated Si [51] due to low work functions of dielectrics [52]. It is therefore indicated that further investigation is necessary for better understanding of the ignition of a plasma in a small gap at high gas pressure.

4 Conclusion

A plasma can be induced by triboelectrification. While the mechanisms of triboelectrification are complicated, influenced by tribological conditions, ignition of a triboplasma in a small gap at high gas pressure can be explained by the field emission of electrons from the cathode due to the combined applied and ionic space charge fields. The breakdown voltage is a monotonically increasing function of the gap to some extent. However, requirement of ionization in a gap leads to a minimum breakdown voltage.

Acknowledgement

This work is supported by a grant from the Danish Research Council (Forskningsrådet for Teknologi og Produktion (FTP) project nr. 274-06-0530).

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